

Astrophysical Applications of Tunable Imaging Filters for the VLT

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Abstract. Tunable imaging filters have been used for a variety of science programmes on the Anglo-Australian and William Herschel Telescopes during the last five years. This contribution describes these novel devices and reviews the science (both Galactic and extragalactic) done with them. Possible strategies for implementing a tunable filter at the VLT are also discussed. Significant scientific potential exists for a tunable filter on the VLT, particularly in the years before such capability becomes available on 8 – 10 m-class telescopes elsewhere.

1 Introduction

The Taurus Tunable Filter (TTF) instruments [3][4] at the Anglo-Australian (AAT) and William Herschel Telescopes (WHT) have seen use in many key areas of astrophysics. Low-redshift science has included studies of brown dwarf atmospheric variability and the identification of optical counterparts to Galactic X-ray sources. At high-redshifts, science has been driven by measurement of the cosmic star-formation history, identification of galaxy clustering around high-redshift QSOs, deep imaging of jet-cloud interactions in powerful radio galaxies, and the detection of a large ionized nebula around a nearby QSO.

This paper describes the characteristics of these instruments and the future role they could play at the VLT.

2 Tunable Filters

2.1 The Taurus Tunable Filter (TTF)

A tunable filter [1] is a special type of Fabry-Perot interferometer incorporating three features that traditional astronomical Fabry-Perot instruments lack.¹ A tunable filter: (1) can move its parallel glass plates over a large range, (2) has anti-reflection coatings optimised over a broad range of wavelengths, and, (3) operates at much narrower plate spacings than traditional devices. These characteristics mean that tunable filters operate at lower resolving powers ($\mathcal{R} = 100$ to 1000) than traditional instruments.

The first Taurus Tunable Filter (TTF; [3][4]) was introduced at the Anglo-Australian Observatory (AAO) in early 1996 by J. Bland-Hawthorn. This red

¹ Note that alternative technologies exist for tunable imaging, although none have been yet been found applications for night-time astronomy [5].

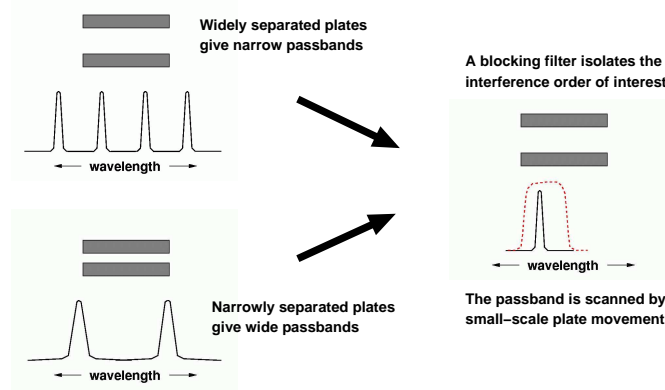


Fig. 1. Tuning the filter to the desired passband width and wavelength.

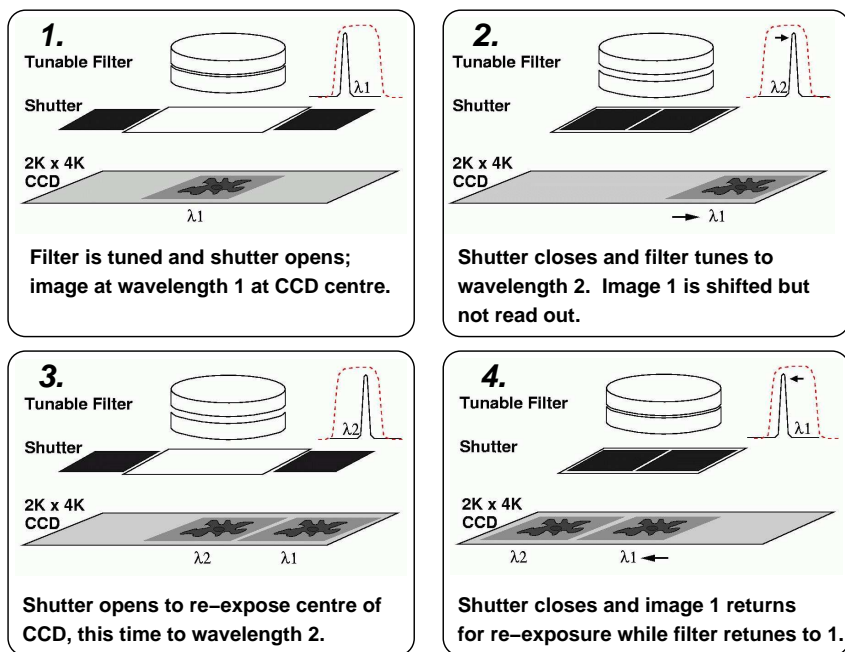
device operates in the range $6500 - 9500 \text{ \AA}$ at the aforementioned resolving powers, thereby giving an adjustable passband width of 6 to 65 \AA . Two years later a second Fabry-Perot coated for $3700 - 6500 \text{ \AA}$ gave the potential for tunable imaging across the full optical range. Since the Fabry-Perot is an interference device, many orders of interference are present simultaneously. Therefore, one needs to use a blocking filter to remove light from all but the one order of interest. There are a dozen different $\sim 200 - 300 \text{ \AA}$ -wide blocking filters used with TTF. More details on the TTF instruments can be found at the AAO's TTF Home Page (<http://www.aao.gov.au/ttf/>).

TTF is used in a cassegrain-mounted focal reducer (Taurus-2), which consists of a simple camera-collimator arrangement with a straight-through optical path. The optical train of Taurus-2 has aperture and focal plane filter wheels at the telescope focus, then the collimator, two further wheels in the parallel beam for the Fabry-Perot and pupil plane masks, the camera and finally the detector. The design of Taurus-2 is very similar to that of the FORS instruments on the VLT. There are identical copies of Taurus-2 at both the AAT and WHT, although Taurus-2 is no longer offered at the WHT. Taurus-2 at the AAT has been scheduled with tunable filters in continuous semesters since 1996.

Tuning is achieved through controlled changes to the separation between the glass plates: initial wavelength and bandpass selection is made by making a large adjustment; subsequent scanning is done through much smaller changes (Fig. 1). The plates are moved and stabilised by electronics attached to the outside of the focal reducer.

2.2 CCD Charge-Shuffling and Tuning

A further development at the AAO was the synchrony of filter tuning with the shuffling of charge on the CCD. The basis of the technique is the use of two or more *different* regions of the *one* CCD frame to image the sky at different wavelengths. Exposure of a particular CCD region/wavelength combination can be



The process repeats many times before CCD is finally read out.

Fig. 2. Synchronising charge-shuffling with tuning of the filter.

made many times before the CCD frame is finally read-out. Figure 2 illustrates the technique. By splicing the multiple exposures of each band, variable conditions during the total imaging time are effectively averaged out. Hence, precise differential photometry is possible in conditions when it otherwise would not. Of course, a portion of the CCD frame must be sacrificed to allow extra room for the shuffle. However, the coincidental introduction of over-sized 2×4 K CCDs at the AAT circumvented this problem.

3 Science from Tunable Filters on the AAT and WHT

Many areas of astrophysics have utilised the tunable filter to undertake a diverse range of science. These projects point the way toward the science possible with a tunable filter on an 8 m-class telescope. The following is a representative (rather than comprehensive) list of recent results with the Taurus Tunable Filter (TTF) on the two 4-m telescopes.

- **Extended Nebula Around a Nearby QSO.** Shopbell, Veilleux and Bland-Hawthorn [12] obtained deep $H\alpha$ imaging of the $z = 0.0638$ quasar MR 2251–178. This revealed ionised gas over a 200 kpc region around the quasar, suggesting its photoionisation of a surrounding HI gas envelope as the cause of the emission, rather than a merger event or interaction.

- **Field Populations of Star-Forming Galaxies.** The scanning ability of TTF was used by Jones and Bland-Hawthorn [11] to search for the emission-line signatures of star-forming galaxies at $z > 0.1$. This narrowband selection found excess numbers of line-emitters over those from traditional broadband-selected redshift surveys, implying higher star-formation densities over these redshifts. Figure 3 shows two TTF-selected galaxies from this survey.
- **Searching for Weather in Brown Dwarfs.** Tinney and Tolley [14] used charge-shuffled time-series imaging of brown dwarfs in two passbands sensitive to variations in effective temperature. Variability was found in one of the two stars surveyed, over observations spanning one-third of its rotation period, indicative of surface features.
- **High-Redshift Gravitationally Lensed Galaxies.** Hewett and collaborators [9] have used the tunable filter to search for gravitationally lensed galaxies at $z \sim 3$. Giant, bulge-dominated $z \sim 0.4$ ellipticals are identified as potential lenses through anomalous emission-lines in 2dF Galaxy Redshift Survey spectra. TTF is tuned to the line to see if a $z \sim 3$ galaxy (being lensed by the elliptical) is responsible for the emission.
- **Time Series Photometry of a Stellar X-Ray Source.** Time-series photometry of the X-ray star V2116 Ophiuchi was undertaken by Deutsch, Margon and Bland-Hawthorn [8]. The tunable filter was tuned to the prominent OI $\lambda 8446$ line in this object, thought to pulse in-phase with the X-ray source. These observations ruled-out any such variability.
- **Galaxy Clustering Around High-Redshift QSOs.** Baker and collaborators [2] tuned TTF to the $z = 0.9$ quasar MRC B0450–221 to search for nearby clustering galaxies. Nine galaxies were found with emission-lines matching [OII] at the redshift of the QSO. Of the five accessible for spectroscopic follow-up, three were positively identified with [OII] and another with a possible line detection.
- **Warm Ionised Gas Around Nearby Radio Galaxies.** TTF was used on the WHT by Tadhunter and collaborators [13] for $H\alpha$ imaging of two radio-galaxies at $z = 0.24$ and 0.09 . Faint emission-line structures were found beyond the radio axes, in addition to the usual bright structures along the radio jets.

Other tunable filter projects currently in progress include imaging of filamentary structures in edge-on spiral galaxies, star-formation regions in nearby elliptical galaxies, $H\beta$ imaging in face-on spirals and $H\alpha$ imaging of nearby galaxy cluster cooling flows. It is likely that such scientific diversity would continue for a tunable filter at the VLT.

4 A Tunable Filter at the VLT

There is currently no tunable filter capability on VLT nor on any 8 – 10 m-class telescopes elsewhere. However, the OSIRIS instrument [7] planned for the 10 m GranTeCan telescope will have tunable imaging, as will the SOAR telescope currently under construction in Chile [6].

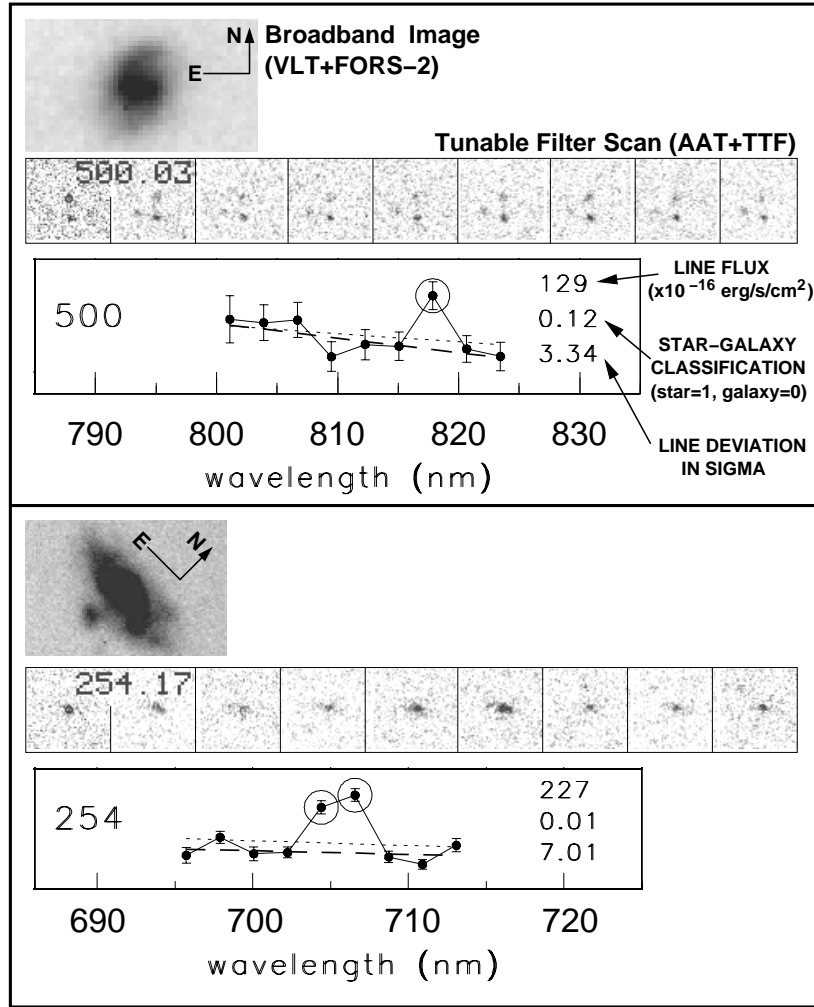


Fig. 3. Example emission-line galaxies found with the TTF for [11].

Tunable filters are commercially available from Queensgate Instruments in several sizes, along with the associated control electronics. While a detailed technical assessment is yet to be done, an informal study has shown that a 116 mm tunable filter can be accommodated in FORs-2 if the upper of the two grism wheels were removed [10]. The full spectroscopic capability of FORs-2 is preserved, although more frequent grism changes are required. In such a case, the echelle mode would be lost from FORs-2 but could be incorporated into FORs-1 instead. Most importantly, no major hardware modifications are required and the control electronics come from Queensgate. Software would need to be upgraded to include control of the instrument, to maximise observing and calibration efficiency. More discussion of the various options available can be found in [10].

A tunable filter on the VLT would have the ability to tune *between* the brightest OH night-sky lines. Moreover, the narrow bandpass would increase the usefulness of FORS during bright-time. As a 3-D survey instrument, a tunable filter would complement the multi-object spectroscopic capabilities of the FORS instruments well. Tunable filters avoid the problems of sky subtraction experienced with other 3-D devices such as IFUs. Furthermore, none of the special reduction techniques used for kinematic Fabry-Perot data are required for tunable filter data because of the much lower spectral resolutions utilised.

5 Summary

Tunable filters have been used for many extragalactic and Galactic stellar programmes at the AAT and WHT over recent years. The ability to synchronise charge-shuffling with tuning of the filter has allowed precise differential imaging to be undertaken by some of these programmes, even in variable conditions. Implementing a tunable filter at the VLT in FORS appears technically feasible. The primary operational change would be more frequent grism installations to maintain all the spectroscopic modes currently available.

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